Geoacoustic Inversion and the Evaluation of Model and Parameter Uncertainties

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Award Number: N00014-05-1-0264
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LONG-TERM GOALS

The development of new geoacoustic inversion methods, their use in the analysis of shallow water experimental data, and evaluation of geoacoustic model and parameter uncertainties including the mapping of these uncertainties through to system performance uncertainties.

OBJECTIVES

The development of methods for estimating the entire posteriori probability densities of the geoacoustic parameters being investigated along with the mapping of these parameter uncertainties through to characterizations of applied interest (e.g. transmission loss), the development of new geoacoustic inversion procedures for use into the kHz frequency regime, the use of ambient noise for initial estimation of seafloor layering structure, and the demonstration of these methods in the analysis of data collected during the Shallow Water 2006 (SW06) experiment.

APPROACH

Geoacoustic inversion involves a number of components: (a) representation of the ocean environment, (b) the inversion procedure selected (e.g. genetic algorithm or simulated annealing) including the forward propagation model implemented, and (c) the estimation of uncertainties associated with the parameter estimates. The latter is critical to facilitate the mapping of these uncertainties into characterizations of applied interest including the prediction of total system performance.

The reporting of geoacoustic parameter estimates without their associated uncertainties is of limited value. Of substantial greater utility is the complete *a posteriori* probability density (in general, the joint density between all parameters being estimated). One significant benefit of obtaining accurate *a posteriori* densities of the geoacoustic parameters is the potential to map these through to characterizations of applied interest (e.g. transmission loss, source detection and localization performance, etc.) in order to quantify those uncertainties as well.

Substantial experience exists in the application of full-field geoacoustic inversion methods. These have been implemented in a number of geometries (e.g. fixed vertical and horizontal arrays, towed arrays, and sonobuoys) and have been shown to work well at low frequencies (< 1 kHz). The application of

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **2009**	2. REPORT TYPE	3. DATES COVERED **00-00-2009 to 00-00-2009**
4. TITLE AND SUBTITLE **Geoacoustic Inversion And The Evaluation Of Model And Parameter Uncertainties**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Scripps Institution of Oceanography,Marine Physical Laboratory,La Jolla,CA,92093**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR’S ACRONYM(S)
		11. SPONSOR/MONITOR’S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release; distribution unlimited**		
13. SUPPLEMENTARY NOTES		
14. ABSTRACT **The development of new geoacoustic inversion methods, their use in the analysis of shallow water experimental data, and evaluation of geoacoustic model and parameter uncertainties including the mapping of these uncertainties through to system performance uncertainties.**		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**6**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

these methods at higher frequencies (into the few kHz frequency regime) is at an early stage. New methods are required which are robust to modest geoacoustic heterogeneity (seafloor parameters as well as bathymetry) and temporal fluctuations (sound speed structure, surface waves, and array dynamics).

Ambient noise provides a natural illumination source that can be used for waveguide parameter estimation purposes. Our specific interest here is in the use of ambient noise to provide initial estimates of seafloor layering structure. Rough estimates of seafloor bathymetry and sediment thickness are needed to parameterize the waveguide model prior to carrying out a geoacoustic inversion procedure regardless of the type of data used for the inversion itself (e.g. source tow data, the radiated signature of ships of opportunity, or ambient noise).

The Shallow Water 2006 experiment took place in July-September 2006 on the outer edge of the New Jersey continental shelf in approximately 80 m deep water. Both narrowband and broadband transmissions (source tows and stations) were made over a wide range of frequencies (50 Hz – 5 kHz) including detailed measurements of seafloor structure and water column variability. These data are available for geoacoustic inversion purposes and the investigation of how nuisance parameter uncertainty (e.g. water column sound speed variability) couples into seafloor parameter uncertainty.

WORK COMPLETED

The Shallow Water 2006 experiment took place in August-September 2006. One component of our analysis has focused on ambient noise using broadband cross-correlations between hydrophones in an array to estimate the time-domain Green's function between them. A comprehensive look was carried out of the noise cross-correlations between HLA/VLA hydrophones in the SWAMI-32, SWAMI-52, and SHARK arrays over the 20-100 Hz band [1]. Both direct path as well as higher-order arrivals could be identified.

A second area of SW06 data analysis has been to estimate Green's functions from cross-correlations of hydrophone pairs observing broadband active sources. Two experimental scenarios have been investigated - a source lowered vertically and one towed horizontally [2].

One application of passive estimation of the time-domain Green's function is in the use of cross-correlations of upward and downward pointing VLA beams observing ambient noise to extract seabed layer structure (i.e. a passive fathometer). The use of adaptive beamforming techniques is advantageous since at lower frequencies the horizontal component of the ambient noise field can be significant. A simplified environmental model has been used to explain mathematically the observation of a sign-inversion in the passive fathometer response using Minimum Variance Distortionless Response (MVDR) beamforming compared to conventional beamforming [3].

Uncertainty in the geoacoustic environment has a significant impact on the estimation of source range and depth. Incorporating environmental parameter uncertainty into the source location problem is done naturally using a Bayesian approach. We have demonstrated this approach using data from the ASIAEX 2001 East China Sea Experiment [4]. First, a geoacoustic inversion provides the probability densities summarizing the uncertainty on critical environmental parameters. Second, these densities then are mapped into uncertainty in the acoustic pressure field and propagated through the Bartlett matched-field processor for source localization. The estimated source location and variability over time are compared with the known source positions.

Finally, we have explored incorporating Kalman and particle filter tracking techniques into the geoacoustic inversion problem [5]. This enables spatial and temporal tracking of environmental parameters and their underlying probability densities, making geoacoustic tracking a natural extension to geoacoustic inversion techniques.

RESULTS

In many cases, it is of interest to estimate geoacoustic parameters over a larger spatial region rather than just the parameters characterizing propagation between a fixed source and receiver (or receiving array) location. Data might be available at a moored vertical receiving array from a towed acoustic sound source or a source might be received by a towed horizontal array. In both cases, the typical approach would be to treat each record of data independently of the others and carry out a full geoacoustic inversion for every record resulting in a sequence of geoacoustic parameter estimates and, in some cases, posteriori probability densities of the environmental parameters. The latter enables the environmental uncertainty to be projected into other waveguide characterizations such as propagation loss and its uncertainty.

Rather than treating the data records independently of one another, the geoacoustic inversion problem can be reformulated as tracking the evolution of these parameters and their associated uncertainties in space and time. This is achieved by merging geoacoustic inversion techniques with tracking algorithms such as the Kalman and particle filters. The interaction between the environmental parameters and the acoustic field can involve a high level of nonlinearity. In addition, the posteriori probability densities of geoacoustic parameters can be non-Gaussian. Thus, geoacoustic tracking requires tracking filters that can handle nonlinear, non-Gaussian systems. We have studied in simulation the suitability of three such filters in geoacoustic tracking– the extended Kalman filter (EKF), the unscented Kalman filter (UKF), and the particle filter (PF) [5].

An example of this approach involves a HLA towed together with a source to map the spatially evolving environment as shown in Fig. 1. Here a 254 m long horizontal line array (HLA) is towed a distance of 300 m behind a source also deployed from the same ship. A nonoverlapping spatial partitioning with each step k representing 500 m is simulated. The waveguide depth is 100 m, source depth is 20 m, HLA depth is 26 m, number of HLA hydrophones is 128, and source frequency is 100 Hz. The environmental parameters tracked are shown in Fig. 2 and include water column (top and bottom), sediment, and bottom sound speeds and sediment thickness, attenuation, and density.

A typical track for each type of filter is shown in Fig. 3 where two PF implementations are included (200 and 5000 particles, respectively). In general, all four filters are able to track bottom sound speed and sediment thickness, sound speed, and density both in slowly and fast changing environments. Since the acoustic field is not that sensitive to the attenuation, it is a relatively poorly determined parameter and the EKF fails to track it while the UKF and the PF-5000 are able to maintain the track (albeit noisy). Similarly, the filters are unable to track the upper water column sound speed value most of the time although on occasion the PF is able to track this parameter.

IMPACT / APPLICATIONS

Geoacoustic inversion techniques are of general interest for the estimation of waveguide parameters thus facilitating system performance prediction in shallow water. Natural transition paths for these results will be the PEO-C4I Battlespace Awareness and Information Operations Program Office (PMW-120) and the Naval Oceanographic Office.

RELATED PROJECTS

This project is one of several sponsored by ONR Code 321OA to participate in the Shallow Water 2006 experiment and participate in the analysis of the resulting data.

PUBLICATIONS

[1] L.A. Brooks and P. Gerstoft, “Green's function approximation from cross-correlations of 20–100 Hz noise during a tropical storm,” J. Acoust. Soc. Am. 125(2): 723-734, DOI: 10.1121/1.3056563 (2009). [published, refereed]

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[5] C. Yardim, P. Gerstoft and W.S. Hodgkiss, “Tracking of geoacoustic parameters using Kalman and particle filters,” J. Acoust. Soc. Am, 125(2): 746-760, DOI: 10.1121/1.3050280 (2009). [published, refereed]

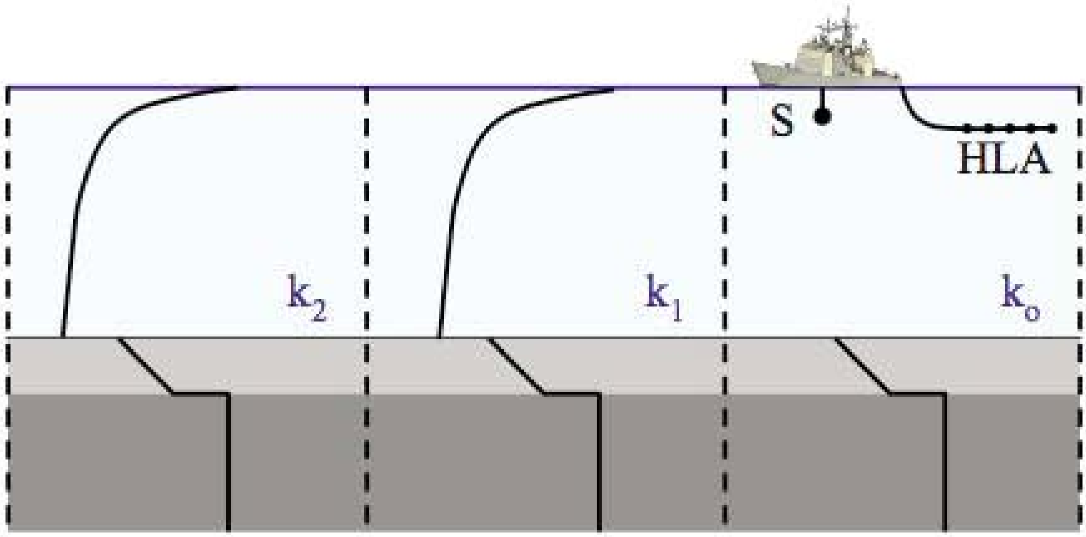

Figure 1. Geoacoustic spatial tracking of range dependent environmental parameters using a towed HLA receiver and a towed source.

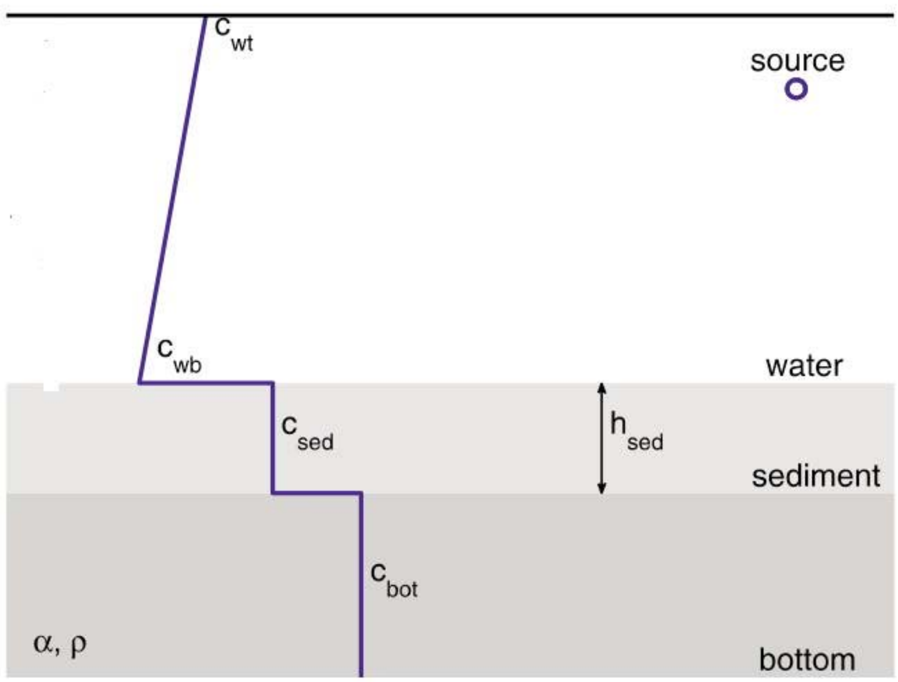

Figure 2. Seven-parameter geoacoustic model used in the geoacoustic tracking simulation. Included are water column (top and bottom), sediment, and bottom sound speeds and sediment thickness, attenuation, and density.

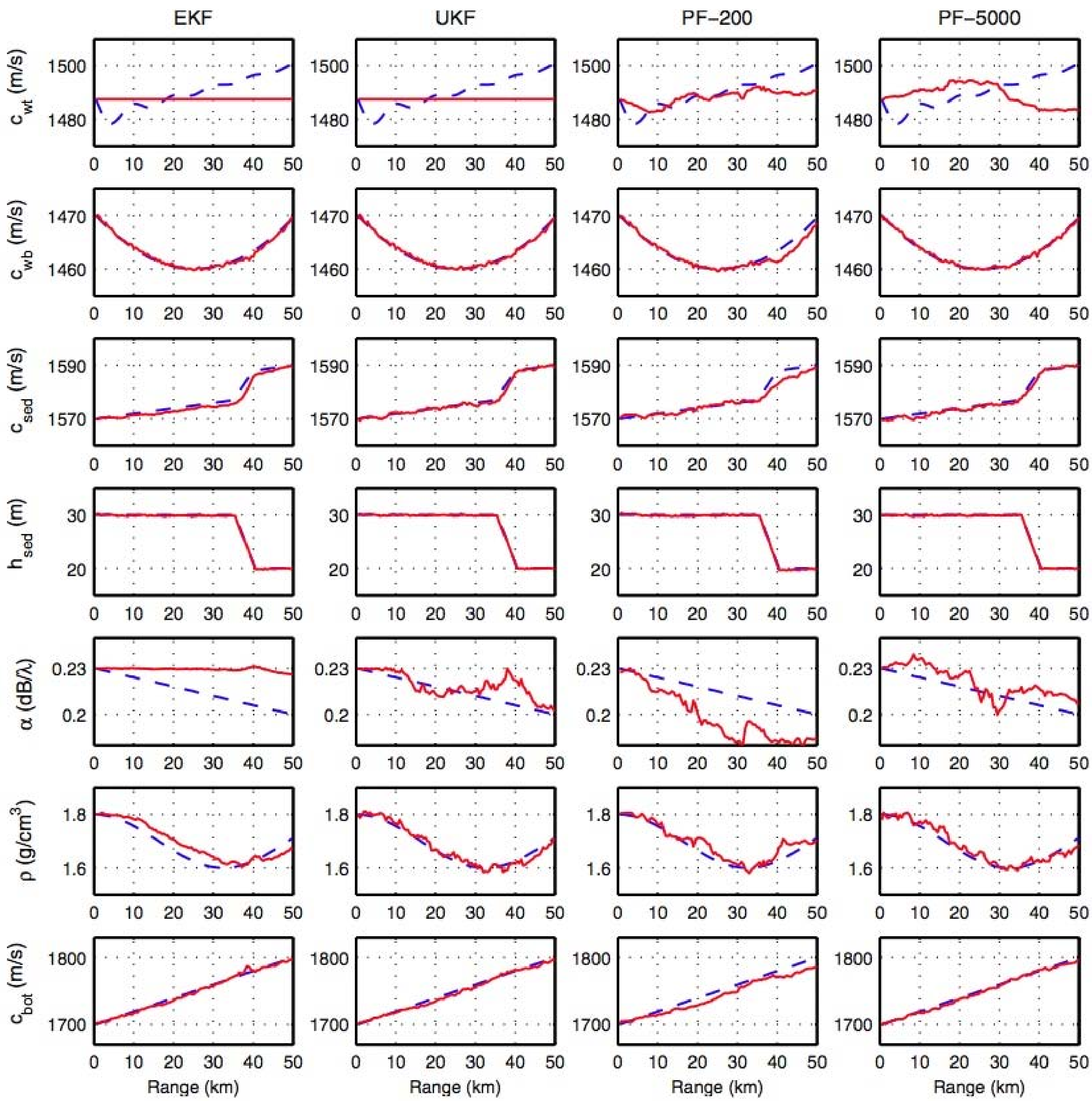

Figure 3. Tracking results of EKF, UKF, PF-200, and PF-5000 for the seven parameter environment using the short range HLA configuration. True trajectories (dashed) are provided along with the tracking filter estimates (solid).